Current induced spin wave excitations in a single ferromagnetic layer

Y. Ji and C. L. Chien

Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland

21218

(February 1, 2008)

Abstract

A new current induced spin-torque transfer effect has been observed in a *single* ferromagnetic layer without resorting to multilayers. At a specific current density of one polarity injected from a point contact, abrupt resistance changes due to current-induced spin wave excitations have been observed. The critical current at the onset of spin-wave excitations depends linearly on the external field applied perpendicular to the layer. The observed effect is due to current-driven heterogeneity in an otherwise uniform ferromagnetic layer.

PACS: 72.25.-b, 75.30.Ds, 73.40.Jn

Typeset using REVTeX

Recently, spin-torque transfer effects have attracted a great deal of attention due to potential device applications [1] as well as the novel fundamental physics it reveals. The magnetic configuration of a system is known to affect its electrical behavior, such as those in anisotropic, giant [2], and tunneling [3] magnetoresistance (AMR, GMR and TMR respectively) effects. Spin-torque transfer is an example of the reverse effect, where an electrical current can alter the magnetic configuration of a system. It has been theoretically predicted [4–6] and experimentally observed [7–10] that at sufficiently high current densities, a spin-polarized current is able to exert a torque on a ferromagnetic entity and switch its magnetization in the low field regime or stimulate spin precession (spin waves) in the same system in the high field regime. Tsoi *et al.* [7,8] first reported on spin wave excitations in Co/Cu multilayers by current injection through a mechanical point contact. Myers *et al.* [9] observed current induced switching in point contacts made by nano-lithography on Co/Cu/Co trilayers. Both magnetization switching and spin precession have been reported by Katine *et al.* [10] in patterned Co/Cu/Co trilayered nanopillars. Other current induced effects have also been observed in Ni nanowires [11] and manganite junctions [12].

To date, most theoretical treatments and experimental observations have featured heterostrctures such as FM/NM multilayers or FM/NM/FM trilayers, where FM=ferromagnet and NM=non-magnetic metal, with a current flowing perpendicular to the layers. There are two considerations that favor the multilayer structures. First of all, these structures provide at least one static FM layer and one free FM layer in the system. The static layer has a fixed magnetization throughout the measurement (realized by shape anisotropy and/or the application of an external field). The static layer, acting as a polarizer, also defines the polarization direction for the current. The free layer is separated from the static layer by a non-magnetic metal. As the spin-polarized current produced by the static layer passes through the free layer, the current carriers transfer their spin angular momenta onto the magnetic moments in the free layer, thereby imparting a torque. The consequence of the torque depends on the polarity of the current. If the electrons flow from the static layer to the free layer, the torque favors a parallel alignment of the FM layers. For electrons flowing

in the opposite direction, the torque favors an anti-parallel alignment of the FM layers. As the current is swept between polarities, at a critical current value, the magnetization of the free layer can be altered between parallel and anti-parallel alignment with respect to the static layer. In the presence of a strong external field (of the order of tesla), however, full magnetization reversal into anti-parallel state becomes unfeasible. Instead, spin waves are stimulated, featuring a precession of spin moments between the parallel and the anti-parallel states.

Secondly, the FM/NM/FM trilayer or FM/NM multilayer structure also exhibits GMR, which becomes a detection mechanism for the magnetization reversal or spin precession. The parallel and the antiparallel configurations of the FM layers define the low and high resistance states respectively in the system. Deviations in configuration, such as that of magnetization reversal, result in changes in the resistance. The spin wave precession can be identified as an increase in the resistance (V/I) or a peak in differential resistance at a certain critical current value in the polarity such that the electrons flow from the free layer to the static layer.

The persuasive rationale for a multilayer structure notwithstanding, multilayer structures have been exclusively employed in experiments for realizing the spin-torque effects. We report in this Letter experimental observation of current induced spin waves in a *single* ferromagnetic layer without heterostructures involving non-magnetic metals. This effect is due to the rapidly degrading current density, which results in magnetic inhomogeneity with a large magnetization gradient within the single layer.

Mechanical point contact technique [13] has been used to inject a current with a current density in excess of 10^9 A/cm^2 from a silver tip into a 3000 Å sputtered Co layer, with an external field up to 9 T applied perpendicular to the Co layer. All the measurements we report in this Letter have been carried out at 4.2 K, using a four-probe method, with $I+$ and $V+$ made on the tip and I- and V- made on the film. For current in the negative polarity, electrons are flowing from the tip into the Co film. We have measured resistance R and differential resistance dV/dI either as a function of current I at a fixed field H or as

a function of field H at a fixed bias current I. The differential resistance dV/dI has been measured using a phase sensitive detection technique with an AC modulation current of 1 μA and 2 kHz.

Figure 1 shows a typical contact that exhibits the unusual behavior of R and dV/dI. The contact resistance is about 28 Ω at zero bias and the external field is 5 T. In the positive polarity, both quantities are slowly varying as a function of current I. The small increase of R or dV/dI at higher bias can be attributed to phonon and magnon scattering [13]. At negative polarity, however, a sharp peak in dV/dI and a prominent step in R (enlarged in the inset) can be seen at a bias current of $I = $ -3.27 mA. The upward jump of R is about 1 Ω, about 3% of the total resistance. The differential resistance changes by more than 100% at the same bias. Beyond the main peak, dV/dI also displays a small upward step at even higher bias. We have studied more than 50 point-contacts that show similar features. The peak in dV/dI or step in R is always present in the negative bias, and never in the positive bias. The peak structure disappears at a field lower than $4\pi M$ (1.7 T), the demagnetizing field of the Co film.

Figure 2(a) shows the results of an Ag/Co contact at different external fields from 2 T to 9 T. All the curves display a peak structure but at different negative bias current. All the curves fall onto the same background, demonstrating that the contact is not altered throughout the measurements. We define the current value corresponding to the peak in dV/dI as the critical current I_c, which, as shown in Figure 2(b), depends linearly on H.

It is interesting to note that Figure 2(b) establishes also a phase diagram for that contact, excluding the low field region where spin waves could not be stimulated. The region above the line represents the excited states with spin precession whereas the region below the line is the ground state where all the spin moments are aligned by the external field. The measurements performed in Figure 2(a) correspond to a scan along a vertical line at a fixed H in Figure 2(b). As the boundary defined by the straight line is crossed, resistance changes (a step in R and a peak in dV/dI) are encountered. The phase diagram so determined is specific to a given contact.

The phase diagram in Figure 2(b) indicates that one can also perform a field scan along a horizontal line and monitor resistance and dV/dI as the phase boundary is crossed. The result of such a scan using a different contact is shown in Figure 3. At a field of 5 T, as the current is scanned from -5 mA to -3 mA, as shown in Figure 3(a), a peak appears in dV/dI at -3.8 mA, signifying the excitation of spin waves beyond this critical value. We then hold the current at -3.0 mA, ramp down the field, and measure R and dV/dI (Figure 3(b-c)). At 2.6 T, a peak in dV/dI and a step in R appear. As shown in Figure 2, as the field is decreased, the critical current value will also decrease. At a lower field, 2.67 T in this case, the critical current value becomes -3.0 mA, hence the dV/dI peak.

We note that the results shown in Figure 1-3 with a single Co layer bear close resemblance to the experimental results of Tsoi *et al.* [7,8] and Katine *et al.* [10] using multilayers. The characteristics also agree well with the theory of Slonczewski [14] in the context of multilayers. The single Co layer geometry that we have used does not contain a static layer/NM/free layer geometry nor a GMR detection mechanism. The multilayer geometry is therefore not a prerequisite for observing the spin-torque transfer effect. In the following, we propose a microscopic picture that accounts for the observed effects, and the salient differences from those observed in multilayers.

The geometry that we use for spin injection through a point contact is schematically in Figure 4. In the negative polarity, where the spin waves are excited, electrons are flowing from the tip into the Co film. The contact size can be estimated from the contact resistance R, the resistivity ρ, and the electron mean free path l using $R=4\rho l/3\pi a^2+\rho/2a$, the Wexler formula, [13,15] which is a combination of Sharvin and Maxwell resistances [15]. The typical resistance value of our contacts is between 10-100 Ω, corresponding to a contact radius of the order of 3-8 nm. As an estimate, at an injection current of 3 mA through such a small contact, the current density is between 1.2×10^9 A/cm^2 and 9×10^9 A/cm^2. However, immediately after the current injection into the Co film, the current spreads and the current density decrease rapidly due to the expanding geometry. Beyond a certain depth, which is marked by a horizontal dashed line in Figure 4, the current density would be too low to excite

spin waves. All the spin moments below would be unaffected by the current and aligned in the external field direction. The region below serves as a static region in the system and provides a source for the spin-polarized carriers. The region above the boundary, where the current density is sufficiently high, acts as the free region. In this manner the single Co layer is separated into a free "layer" immediately below the point contact and a fixed layer for the remainder of the Co layer. The thickness of the "free" layer is determined by the current distribution underneath the point contact. In this sense, the single Co film is divided into two regions by a dynamic process, rather than physically separated by the insertion of a non-magnetic layer as in Co/Cu/Co trilayers.

Electrons from the tip first flow through the free region and then enter the static region. As discussed earlier, in this polarity the current induced torque onto the free region tends to deflect the spin moments from the parallel alignment, causing spin precession. The resistance step or dV/dI peak, which is considered the signature of spin precession, can be understood as such. As the precession is excited, spin moments in the free region will have a small tilt angle with respect to the spin in the static region. Given the small length scale, the magnetization gradient would be extremely high. As the charge carriers moving from the free region to the static region, their spin moments could not relax adiabatically. Instead, spin-dependent scattering occurs, giving rise to a high resistance state.

The above model accounts for the experimental results using a single FM layer well. It also implies certain features that are different from multilayers. Slonczewski [14] has calculated the current threshold of spin excitations in the context of point contact current injection into a laterally unbounded FM1/NM/FM2 structure, with a field perpendicular to plane. There are two distinct origins of current threshold requirements. One is due to energy loss through radiation from the central excited region under the contact to the rest of the FM1 layer. This term is proportional to exchange stiffness and the thickness of FM1 layer. The other is attributed to the alignment of the effective field, which includes the external field, the demagnetizing field, the anisotropy field and the exchange field from FM2 layer. The current induced torque has to be large enough to overcome the effective field

and viscous damping. So the field dependent term is proportional to the effective field, the Gilbert damping coefficient, and the total magnetic moments in the excitation region. In the case of a single Co layer, both terms imply a higher threshold current than those in multilayers. The propagation of energy will no longer be constricted in a very thin FM1 layer. Instead the excited region will dissipate energy through exchange interaction into the entire 300 nm thick Co film. The exchange field experienced by the excited region is also much larger, without separation by a non-magnetic metal between the free layer and the static layer.

The dV/dI peaks that we have observed occur in a negative bias voltage between 100 mV to 200 mV in Figure 2(a). The estimated current density is 5-8$\times 10^9$ A/cm^2, which is considerably higher than the value of 10^8 A/cm^2 in trilayered pillars [10], and the value of about 1$\times 10^9$ A/cm^2 for multilayers [7,8]. In the latter, since the current injected from a point contact spreads out in the multilayers, perhaps only the top layers can be excited and the rest of the layers remain fixed as a polarizer.

In conclusion, we report spin wave excitations in a single ferromagnetic layer by high-density current injection through a point contact. Without a multilayer structure involving non-magnetic metal or a nanolithographically patterned trilayer nano-pillar, we have observed spin precession, albeit at a higher current density. The spin precession occurs in a constricted region underneath the point contact. The resistance changes, signatures of spin-wave excitations, are attributed to spin dependent scattering due to a localized large magnetization gradient. The effects that have been observed in single ferromagnetic layers imply that similar effects could also appear in multilayers, even though the multialyers have been designed to create magnetic heterogeneity.

REFERENCES

[1] J. Slonczewski, *United States Patent #5,695,864, Dec 9, 1997*.

[2] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazeles, *Phys. Rev. Lett.* **61**, 2472 (1988).

[3] J. S. Moodera, Lisa R. Kinder, Terrilyn M. Wong, and R. Meservey, *Phys. Rev. Lett.* **74**, 3273 (1995).

[4] L. Berger, *Phys. Rev. B* **54**, 9353 (1996).

[5] J. Slonczewski, *J. Magn. Magn. Mater.* **159**, L1 (1996).

[6] Ya. B. Bazaliy, B. A. Jones, and S.-C. Zhang, *Phys. Rev. B* **57**, R3213 (1998).

[7] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck. V. Tsoi, and P. Wyder, *Phys. Rev. Lett.* **80**, 4281 (1998).

[8] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, V. Tsoi, P. Wyder, *Nature* **406**, 46 (2000).

[9] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, *Science* **285**, 867 (1999).

[10] J. A. Katine, F. A. Albert, R. A. Buhrman, E. B. Myers and D. C. Ralph, *Phys. Rev. Lett.* **84**, 3149 (2000).

[11] J.-E. Wegrowe, D. Kelly, Y. Jaccard. PH. Guittienne and J.-PH. Ansermet, *Europhys. Lett.* **45**, 626 (1999).

[12] J. Z. Sun, *J. Magn. Magn. Mater.* **202**, 157 (1999).

[13] A.G. M. Jasen, A. P. van Gelder, P. Wyder, *J. Phys. C.* **13**, 6073 (1980).

[14] J. Slonczewski, *J. Magn. Magn. Mater.* **195**, L261 (1999).

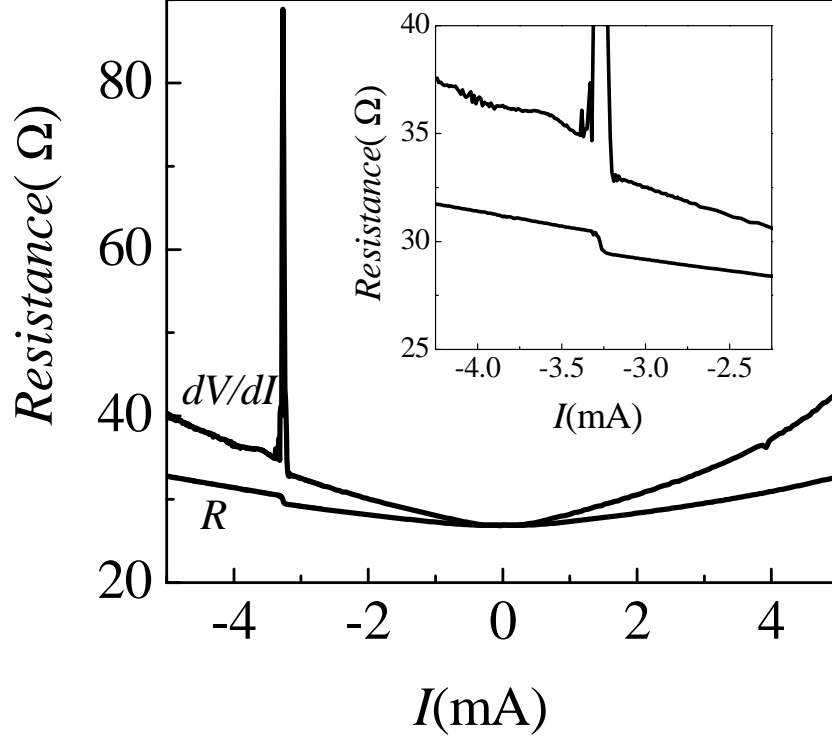[15] G. Wexler, *Proc. Phys. Soc. London* **89**, 927 (1966).

FIG. 1. The *R-I* and *dV/dI-I* plots for a point contact between an Ag tip and a Co film subject to an external field of 5 T perpendicular to the Co layer at 4.2 K, showing the peak (or step) at bias current *I*=- 3.27 mA, enlarged in the inset.
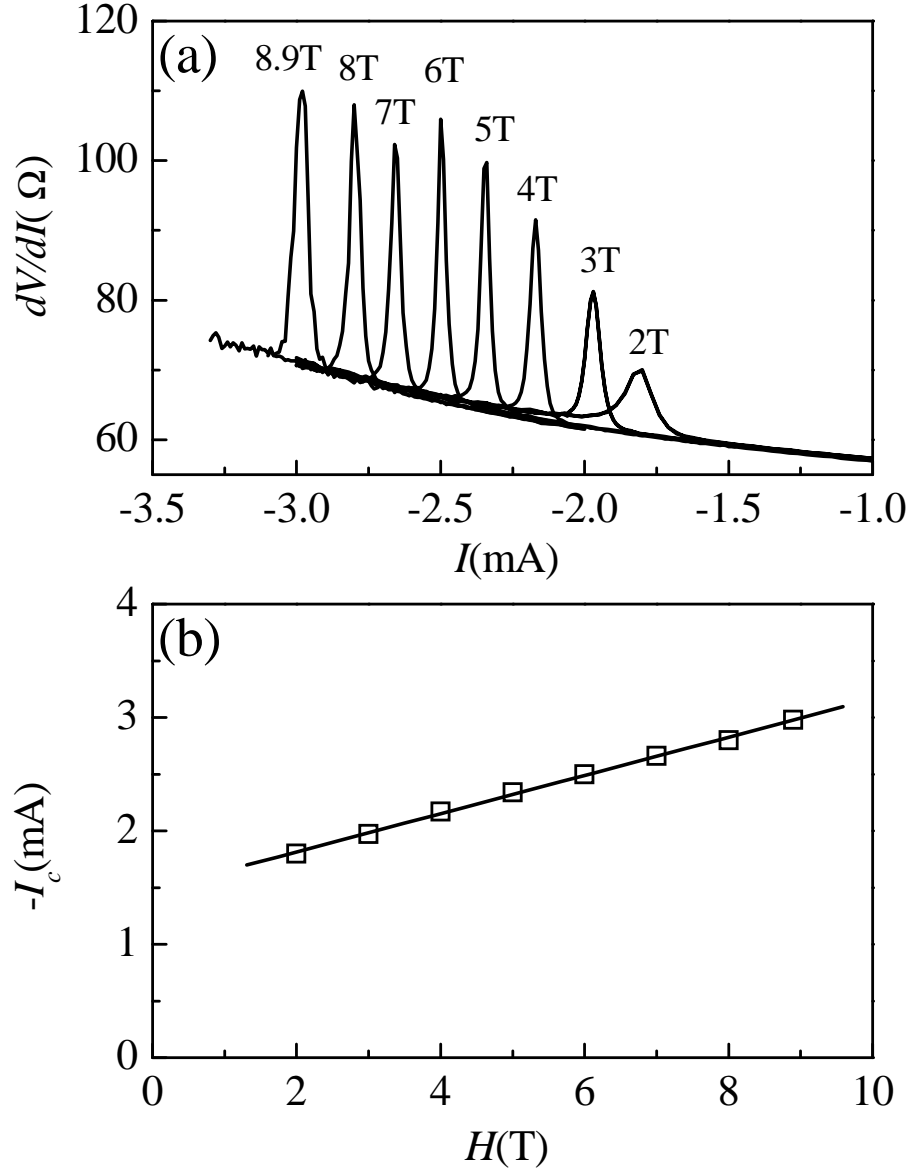
FIG. 2. (a) The dV/dI-I plots at different fields for an Ag/Co point contact at 4.2 K. The current value at the peak position, defined as I_c, depends linearly on the external field as shown in (b).
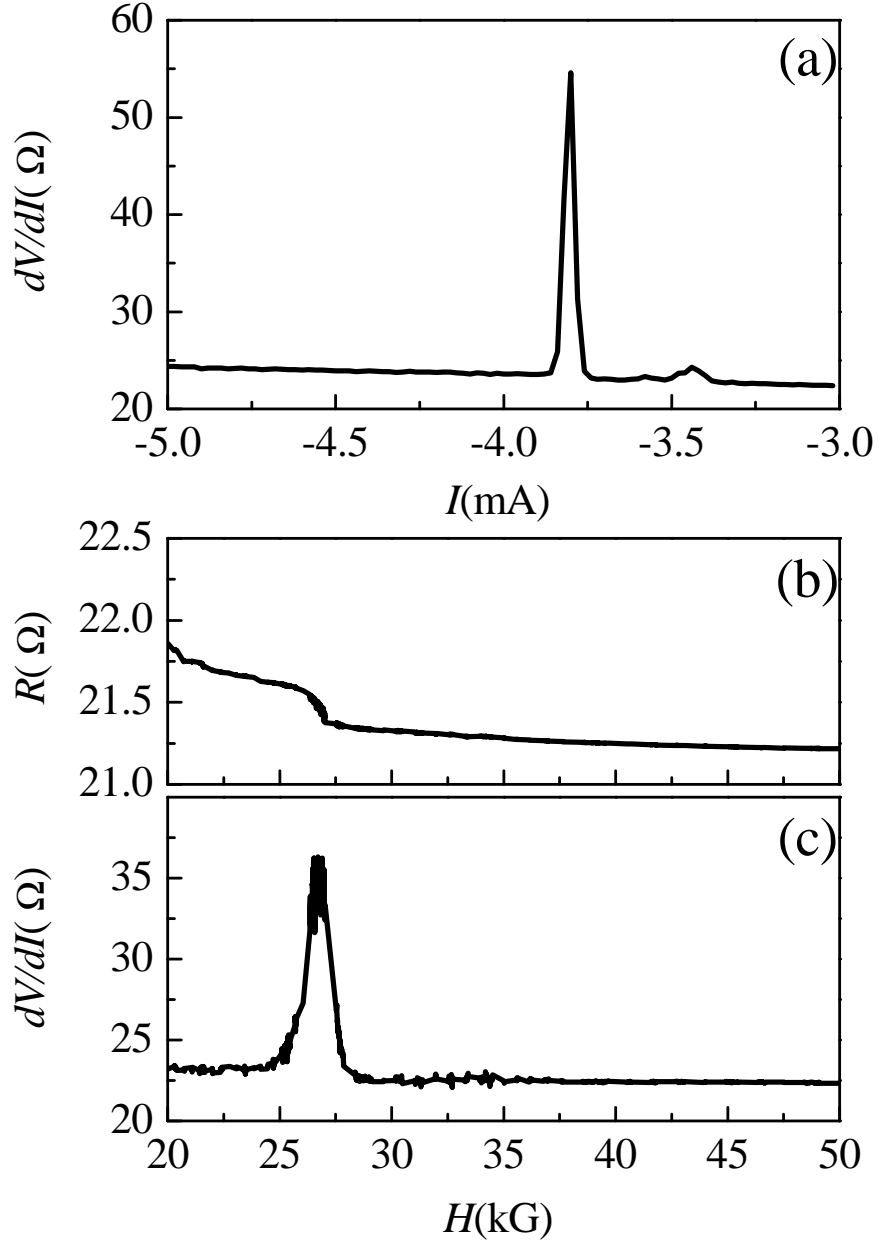
FIG. 3. Resistance and dV/dI of an Ag/Co point contact at 4.2 K. (a) Vary the current from - 5 mA to - 3mA in a fixed field of 5 T, (b)(c) Vary the magnetic field at a fixed current of - 3 mA.
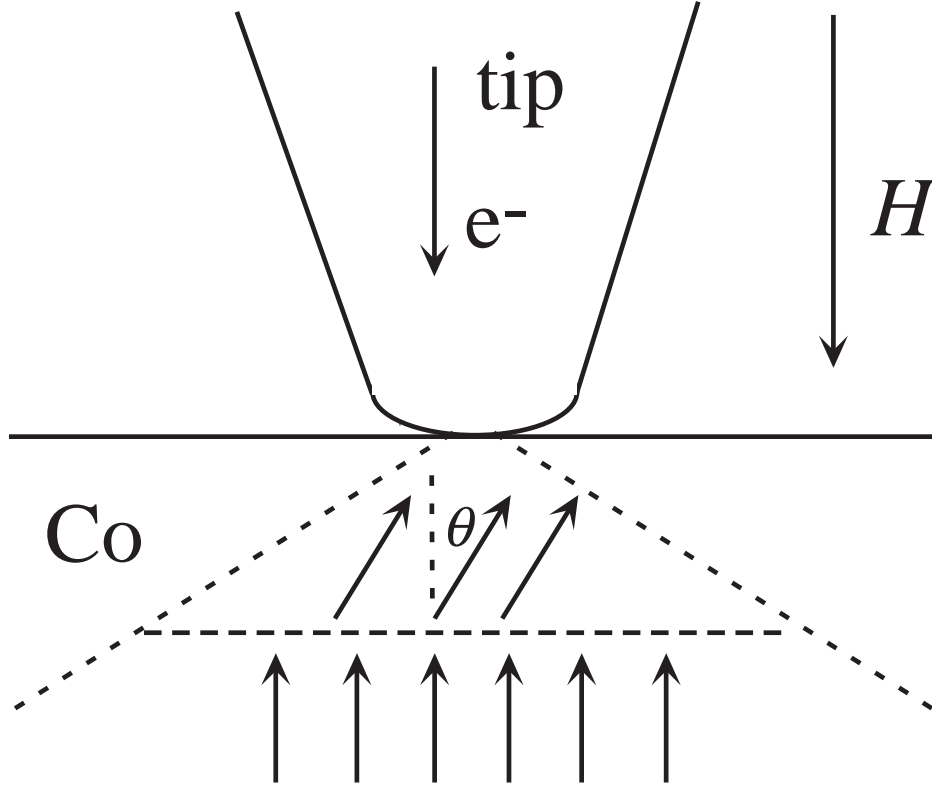
11

FIG. 4. A microscopic picture of a point contact between an Ag tip and a Co film with an external magnetic field applied perpendicular to the Co layer. On entering the Co film, electrons first pass through a localized "free region" right underneath the tip and before entering the "static region" as the current spread out. The horizontal dashed line mark the boundary between the free and static regions.